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Plueddemann, Albert J.

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Woods Hole Oceanographic Inst
360 Woods Hole Road
Woods Hole, MA 02543-1541

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Steven G. Ackleson
Office of Naval Research
Ballston Centre Tower One
800 N. Quincy St
Arlington, VA 22217-5660

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14. ABSTRACT

Manipulative field experiments were performed in which optically-active $CaCO_3$ coccoliths (from Cretaceous chalk) were injected into the mixed layer to create a "chalk patch". Experiments were performed at two stations, one mesotrophic and one eutrophic, during two times of the year, June and November. The scientific rationale for this experiment was that by seeding a patch, the particle production term was known absolutely, so that effort could be focused on the particle loss terms. Each patch was surveyed quasi-synoptically for several days, as the optical and physical properties evolved. Each experiment included spatial and aerial surveys, deployment of drifting sediment traps, measurements of grazing and aggregation from in-situ samples and determination of the distribution of dissolved organic matter. The Woods Hole Oceanographic Inst. contributions to the field work focussed on three issues: (1) Determining the surface forcing during and after each chalk deployment, (2) Tracking the chalk patch with Lagrangian drifters, and (3) Determining the temporal evolution of stratification and shear in the upper ocean. The results demonstrate how important physical conditions are to the initiation and retention of a highly reflective coccolithophore bloom.

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a. REPORT	b. ABSTRACT	c. THIS PAGE	Unclassified Unlimited	4	19b. TELEPHONE NUMBER *(include area code)* (508) 289-2789

Final Report

Chalk-Ex: Transport of Optically Active Particles from the Surface Mixed Layer

Albert J. Plueddemann
202A Clark Lab, MS-29, Woods Hole Oceanographic Institution, Woods Hole, MA 02543-1541
phone: (508) 289-2789 fax: (508) 457-2181 email: aplueddemann@whoi.edu

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Long Term Goals

To determine the mass balance of optically active particles within the ocean surface boundary layer and identify the processes responsible for particle redistribution.

Objectives

1. Perform manipulative experiments in which a known quantity of optically active particles is introduced at the surface and tracked over time and space. This approach effectively removes uncertainty in the production term of the mass balance equation.

2. Identify and quantify the relevant physical and biological processes that remove optically active particles from the mixed layer (e.g., vertical mixing, sinking, dissolution, aggregation, and grazing-related "repackaging" into fecal pellets).

Approach

The focus of the Chalk-Ex project was a sequence of multidisciplinary field experiments done in cooperation with W. Balch, C. Pilskaln and J. Goes (Bigelow Lab for Ocean Sciences) and H. Dam and G. McManus (University of Connecticut). Patches of optically-active particles were created within the mixed layer by dispersal of ground Cretaceous chalk ($CaCO_3$) from the stern of a research ship. Two deployments were completed during each of two cruises: November 2001 and June 2003. Each deployment used ~13 tons of chalk to make a patch of ~2 km^2. The first deployment of each cruise was at a eutrophic site within the Gulf of Maine, and the second was at a mesotrophic site over the continental slope south of Georges Bank. Patch evolution was monitored using a combination of time series and spatial survey measurements over periods of 2–4 days. Each experiment included chalk deployments (Balch), spatial and aerial surveys (Balch/Plueddemann), deployment of drifting sediment traps (Pilskaln), measurements of grazing and aggregation from in-situ samples (Dam/ McManus) and determination of the distribution of dissolved organic matter (Goes). The WHOI contributions to the field work focussed on three issues: (1) Determining the surface forcing during and after each chalk deployment, (2) Tracking the chalk patch with Lagrangian drifters, and (3) Determining the temporal evolution of stratification and shear in the upper ocean.

Tasks Completed

The first Chalk-Ex cruise was completed during 10–19 November 2001 on the R/V *Endeavor* out of Portland, Maine. Two sites were occupied. The north site was near 43°50'N, 67°45'W and the south site was near 39°45'N, 67°45'W. The second cruise was completed during 12–22 June 2003, again on the R/V *Endeavor* out of Portland. The same two sites were occupied. Approximately 13 tons of

$CaCO_3$ were injected at each site on each cruise. Following the chalk deployments, the interdisciplinary research team conducted a variety of operations while the patch was being tracked and mapped.

Surface fluxes of heat and momentum were determined from shipboard meteorological observations using bulk formulas. Tracking of the patch was done by means of Lagrangian drifters which followed the near-surface flow (upper 1–10 m, depending on the drogue configuration) and transmitted their position in near real-time. Drifter positions were available onboard the ship during the experiment, and served as a reference for adjusting the survey legs to intersect the patch. Position information was also transmitted via Argos satellite, and these more complete data were used to produce high quality drift tracks for post-cruise analysis. Upper ocean hydrography was measured from an instrumented drifter deployed near the center of the patch. This drifter consisted of a small surface buoy with instrumentation for measuring temperature, salinity, and velocity suspended below. Subsurface measurements were made over the upper 100 m for the November experiment, where relatively deep mixed layers were anticipated. For the June deployment, instrumentation was "compressed" into the upper 60 m. Additional temperature sensors available for the June experiment were attached to the Lagrangian drifters to better resolve horizontal variability.

Results

The environmental conditions during each of the four experiments exerted a strong influence on chalk dispersal. These conditions are summarized in Fig. 1 in terms of the values of wind stress, net surface heat flux (Qnet) and mixed layer depth (MLD) averaged over the chalk deployment period. The influence on chalk distribution for each deployment is summarized briefly below.

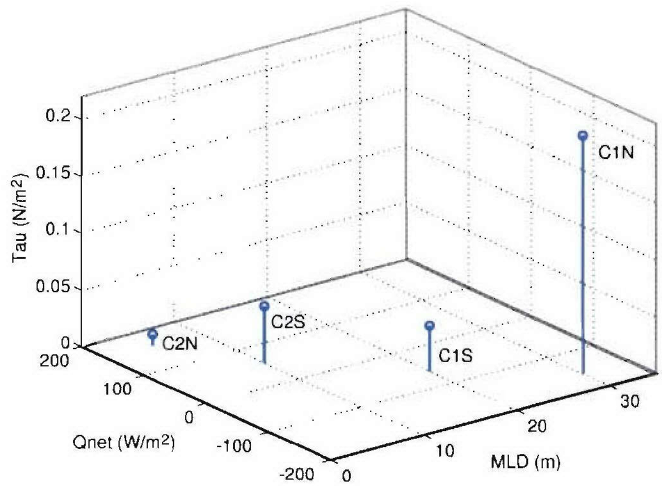
November 2001, North Site (C1N): Surface conditions (Fig. 2: wind speed 7–14 m/s, average heat loss 315 W/m^2) favored rapid vertical mixing. The mixed layer depth (MLD) was about 30 m at the time of chalk injection, deepening to 50–70m depth within 12 h (Fig. 3). As a result, the chalk was rapidly diluted immediately after injection, and proved difficult to detect.

November 2001, South Site (C1S): Conditions during and following chalk injection (wind speed 4–7 m/s, average heat gain 40 W/m^2) were more favorable for chalk detection. The MLD was near 10 m during injection, followed by modest deepening and then shoaling to about 10 m due to horizontal advection. The MLD dictated the initial penetration depth of the chalk, but patch development during the first 48 hours was controlled primarily by horizontal advection during a period of restratification.

June 2003, North Site (C2N): Surface conditions wind speed 3–5 m/s, strong diurnal heating) resulted in a relatively steady MLD of less than 10 m during the first 2 days of operations. A sharp thermocline was seen near20 m depth, and strong, high-frequency (10–40 min) internal waves were associated with this interface. Winds began to increase about 18 h after chalk deployment, eventually driving the MLD deeper. Increased vertical mixing and near-surface shear associated with this wind event spread the chalk to undetectable levels by the time of the final survey at about 57 h after deployment.

June 2003, South Site (C2S): Conditions just after chalk injection (wind speed 4–6 m/s, strong diurnal heating) were favorable for maintaining a shallow MLD (less than 10 m). Winds were variable (1–10 m/s) over the next 3 days, during which the MLD varied from 5–20 m. The thermocline at the south site was more diffuse than at the north site, and internal wave activity was not as pronounced. The patch at the southern site was detectable for at least 48h after injection.

Figure 1. Comparison of environmental conditions during the deployment period for each experiment. [A 3-D plot shows the relative values of mixed layer depth, net heat flux, and wind stress for each of four experiments.]



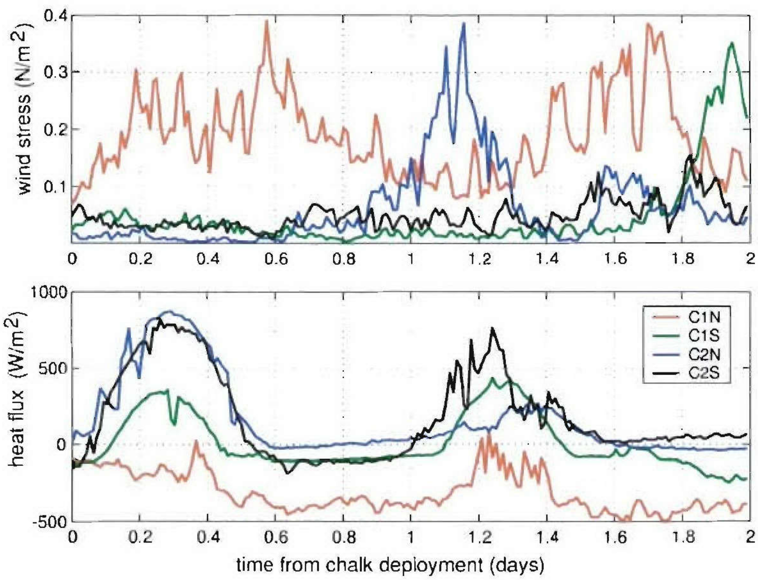
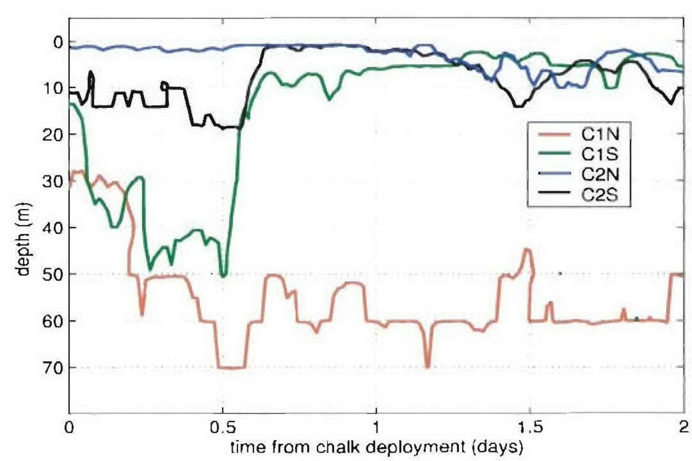


Figure 2. Comparison of wind stress (upper panel) and heat flux (lower panel) for the first two days of each of the four experiments. [Two panels show time series for the four ChalkEx experiment, highlighting differences in forcing conditions, as described in the text.]

Figure 3. Mixed layer depth variability for the first two days of each of the four experiments. [Mixed layer depth is plotted vs. time for the four ChalkEx experiments, highlighting differences in stratification, as described in the text.]



Impact for Science

The experiments were designed to quantify the major loss terms for optically active particles and improve understanding of the evolution of the optical field and predictions of underwater visibility. To our knowledge, this was the first controlled, manipulative field experiment in which the production term of optically-active particles could be defined, significantly reducing the uncertainty of the net loss rates of particles from the mixed layer. The high refractive index of CaCO3 allowed high reflectance patches to be created from modest amounts of material. Thus our deployments could be simultaneously detected using space-based remote sensing in three of the four patches (the exception was due to cloudiness obscuring the patch from the satellite). The results demonstrate how important physical conditions are to the initiation and retention of a highly reflective coccolithophore bloom.

Relationship to Other Programs

The ChalkEx project was a collaboration among W. M. Balch, C. Pilskaln, H. Dam, G. McManus, and A. Plueddemann. During year 1 of the project, the NASA MODIS team funded Balch to do chalk seeding studies for calibration/validation of the MODIS suspended calcite algorithm. The NASA project paid for the 26 T of chalk and some of the ship time for the November 2001 experiments. A DURIP Grant to J. Vaughn (U. New England) and Balch provided equipment that was utilized in the ChalkEx experiments. A small surface buoy design developed for the Remote Environmental Monitoring UnitS (REMUS) vehicle program was adapted for use with the instrumented drifter. Instrumentation obtained by WHOI as a part of an NSF Major Research Instrumentation grant was used to upgrade the T-only measurements originally proposed for the instrumented drifter to T/S measurements.

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